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REVIEW ARTICLE

Pfirrmann grading of intervertebral disc degeneration: Morphological assessment, treatment response, and emerging quantitative MRI approaches

Chao Ge[1†], Mingwei Wang[2†], Bifeng Fu[2], Tao Wang[2], Zihan Qi[2], Qiujing Hao[2], Weimin Wang[2*], and Pengtao Huang[2*]

[1]Department of Beiyang Outpatient Department, Tianjin University Hospital, Tianjin, China

[2]Department of Traditional Chinese orthopedics and Traumatology Ward, National Clinical Research center for Chinese Medicine, First Teaching Hospital of Tianjin University of Traditional Chinese Medicine, Tianjin, China

Abstract

Introduction: Intervertebral disc degeneration (IVDD) is a major cause of low back pain, and magnetic resonance imaging (MRI) is the primary tool for its assessment. Among these, the Pfirrmann classification is widely used in clinical practice and research due to its standardization and practicality.

Objective: This paper reviews MRI-based methods for assessing IVDD, focusing on the relationship between the Pfirrmann classification and the efficacy of conservative treatment, surgical treatment, and regenerative therapy.

Methods: This narrative review searched PubMed, Web of Science, and Embase for literature published from January 2000 to June 2026 using terms including "disc degeneration," "Pfirrmann classification," and "quantitative magnetic resonance imaging," with inclusion criteria applied.

Results: The Pfirrmann classification reflects changes in intervertebral disc morphology and signal intensity; however, it does not fully correlate with clinical symptoms or treatment response, suggesting that pain and treatment efficacy are influenced by multiple factors, including inflammation, nerve root involvement, and endplate changes. In clinical practice, patients with mild to moderate degeneration typically respond better to conservative treatment, and pre-operative grading aids in surgical decision-making. Advances in quantitative MRI techniques—such as T2 mapping, T1ρ, and diffusion kurtosis imaging—along with developments in artificial intelligence, have provided new tools for early identification of degeneration and improved accuracy in predicting treatment outcomes.

Conclusion: The Pfirrmann grading system remains the foundation for IVDD assessment; however, future work will need to integrate quantitative imaging, biomarkers, and clinical phenotypes to establish a comprehensive, multi-parameter model that enables more precise treatment outcome prediction and personalized therapy.

Keywords: Intervertebral disc degeneration; Pfirrmann grading; Quantitative magnetic resonance imaging; Treatment response; Artificial intelligence

[†]*These authors contributed equally to this work.*

***Corresponding authors:**
Pengtao Huang (15022197446@163.com);
Weimin Wang (tjyfyxuanchuan@sina.com)

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1. Introduction

Intervertebral disc degeneration (IVDD) is one of the leading causes of low back pain (LBP) and imposes a significant socioeconomic burden worldwide. Magnetic resonance imaging (MRI) is the primary tool for evaluating IVDD, and the Pfirrmann classification system is the most widely used semi-quantitative assessment method in clinical practice. However, the relationship between imaging-based degeneration severity and patients' clinical symptoms and treatment response is complex and often inconsistent.[1,2] Key factors in IVDD include degeneration of functional cell populations within the nucleus pulposus and annulus fibrosus, an imbalance between extracellular matrix synthesis and degradation, and reduced proteoglycans and tissue dehydration; these changes collectively impair the intervertebral disc's ability to withstand mechanical loads.[3] Research indicates that, at the molecular level, mechanical stress, oxidative stress, inflammatory responses, and impaired autophagy are all considered key factors driving the onset and progression of IVDD (Figure 1).[4-8]

Due to its excellent soft-tissue contrast and the absence of ionizing radiation, MRI has become the gold standard for diagnosing and evaluating IVDD. In clinical practice, to standardize the assessment of IVDD severity, a five-grade grading system based on T2-weighted sagittal images was introduced in 2001. This system primarily classifies lesions based on disc signal intensity, disc height, the distinction between the nucleus pulposus and the annulus fibrosus, and internal structure; it has been widely adopted due to its simplicity and ease of use.[9] However, the original five-grade system has limited discriminatory power when evaluating elderly populations or subtle degenerative differences. Consequently, researchers proposed a modified eight-grade classification system to provide a more refined assessment.[10] Although the Pfirrmann grading system has been successful in morphological evaluation, it is essentially a semi-quantitative observational method that struggles to capture biochemical and microstructural changes in the early stages of degeneration. In recent years, quantitative MRI techniques such as T1, T2, and T2 mapping, T1ρ relaxation time measurement, diffusion kurtosis imaging (DKI), and glycosaminoglycan chemical exchange saturation transfer (GAG-CEST) imaging have advanced rapidly.[11] These techniques provide objective, reproducible, quantitative data on water content, proteoglycan concentration, and integrity of the collagen network within intervertebral discs, enabling detection of pathophysiological changes before morphological alterations occur.[12,13]

However, there is no simple linear relationship between the severity of IVDD as diagnosed by imaging and the patient's clinical symptoms (particularly pain) and treatment outcomes.[14] Many individuals with severe disc degeneration on imaging may be completely asymptomatic, while some patients with mild imaging findings may suffer from unbearable chronic pain. This imaging–clinical mismatch poses a significant challenge for treatment decision-making. Both doctors and patients urgently need to know whether the degree of degeneration, as assessed using the Pfirrmann classification, can predict the clinical efficacy of different treatment methods, thereby providing a basis for selecting the most appropriate treatment plan. This paper explores this core issue in depth. Adopting a narrative approach and drawing on a review and selection of the literature, it traces the development of the Pfirrmann classification, quantitative MRI techniques, and artificial

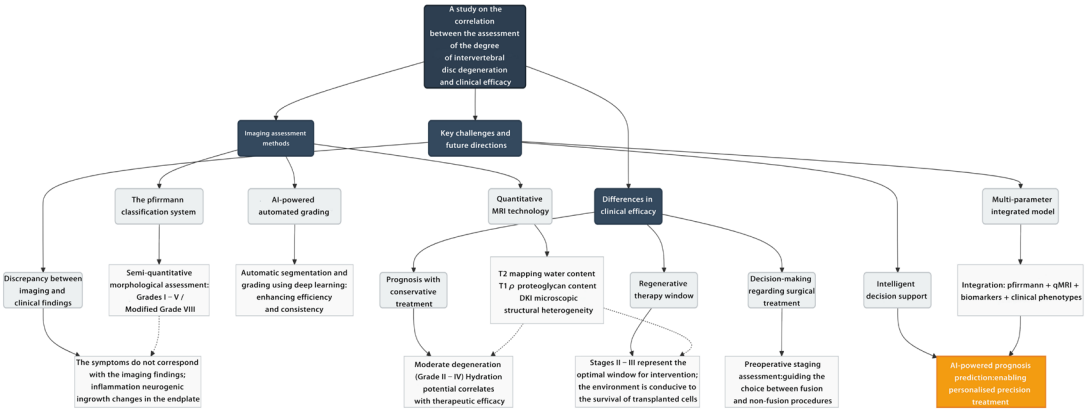


Figure 1. Map of intervertebral disc degeneration
Abbreviations: AI: Artificial intelligence; MRI: Magnetic resonance imaging.

intelligence (AI)-assisted assessment, while also examining the clinical context of treatment-related radiological changes. The aim is to advance the precise diagnosis and personalized treatment of IVDD.

2. Imaging techniques for the assessment of intervertebral disc degeneration

2.1. The Pfirrmann classification is the cornerstone of clinical assessment

The Pfirrmann grading system is currently the most widely used semi-quantitative assessment standard for IVDD internationally. Based on T2-weighted sagittal images from routine lumbar MRI, this system classifies degeneration into five grades according to disc signal intensity (Figure 2), the boundary between the nucleus pulposus and the annulus fibrosus, disc height, and signal homogeneity. Due to its intuitive and user-friendly nature, this system is widely used in clinical practice to assess the degree of degeneration and for follow-up observations.[15] However, as research has progressed, its limitations have gradually become apparent. For example, in elderly populations with concentrated degeneration, most intervertebral discs are classified as grades III to V, rendering the system inadequate for distinguishing subtle differences within severe degeneration. To address this issue, Griffith *et al.*[10] developed a modified eight-grade classification system (Figure 3). The revised eight-grade Pfirrmann classification system provides a more detailed morphological classification, particularly in older populations, by incorporating additional details such as the endplates, osteophytes, and annulus fibrosus morphology, thereby enhancing its discriminatory power and reliability in populations with severe degeneration.[16]

2.2. Quantitative magnetic resonance imaging technology accurately detects microscopic changes

To overcome the subjectivity and semi-quantitative limitations of the Pfirrmann classification, and to detect the pathophysiological changes associated with IVDD earlier and more precisely, a variety of quantitative MRI techniques have emerged. These techniques advance MRI from "visualizing morphology" to "measuring composition," providing clinicians with more in-depth pathophysiological information, thereby enabling more accurate diagnosis and personalized treatment. Some

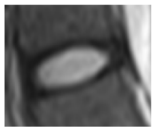
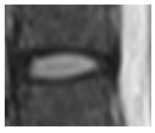
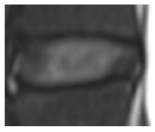
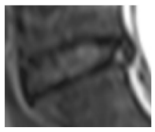
Images	Grade	Intervertebral disc height	Distinguishing between the nucleus and the annulus fibrosus	Signals within the intervertebral disc
	I	Normal	Clear	Uniform high signal
	II	Normal	Clear	Uneven high signal
	III	Slight decrease	Blurred	Uneven moderate signal
	IV	Moderate reduction	Disappear	Uneven low signal
	V	Significantly reduced	Disc collapse	Uneven low signal

Figure 2. Image of the five-grade Pfirrmann classification

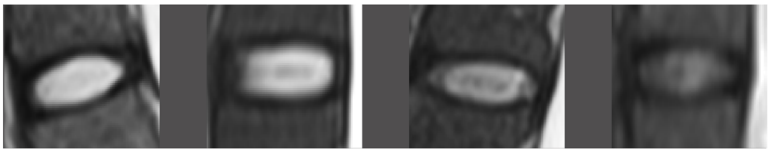
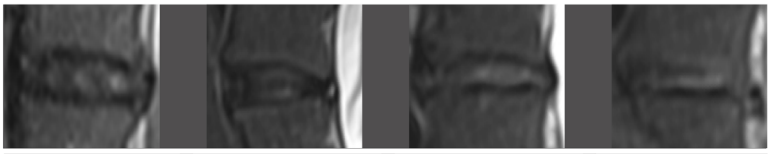
Images				
Grade	I	II	III	IV
Intervertebral disc height	Normal	Normal	Normal	Normal
Distinguishing between the nucleus and the annulus fibrosus	Clear	Clear	Clear	Blurred
Signals within the intervertebral disc	Uniformly hyperintense, equal to CSF	Hyperintense > presacral fat <CSF	Hyperintense < presacral fat	Mildly hyperintense
Images				
Grade	V	VI	VII	VIII
Intervertebral disc height	Normal	30% reduction	30%–60% reduction	> 60% reduction
Distinguishing between the nucleus and the annulus fibrosus	Blurred	Blurred	Blurred	Blurred
Signals within the intervertebral disc	Hypointense (equal to outer fibers of anulus)	Hypointense	Hypointense	Hypointense

Figure 3. Image of the eight-grade Pfirrmann classification
Abbreviation: CSF: Cerebrospinal fluid.

studies have attempted to combine MRI with deep learning radiomics to construct automated classification models for lumbar disc degeneration. These models can reduce inter-observer variability, improve follow-up efficiency, and complement quantitative parameters, thereby enhancing the accuracy of early identification and stratified management of IVDD. For quantitative MRI, such automated strategies are expected to complement quantitative parameters such as T2, T1ρ, and DKI, and combining the two may further improve the accuracy of early identification and stratified management of IVDD.[17] The techniques are described as follows:

(i) T2/T2 mapping: Its advantage lies in the fact that it reflects the degree of freedom of water molecules within the tissue and the structure of collagen through the spin decoherence rates of water molecules in different microenvironments, thereby providing non-invasive insight into changes in the intervertebral disc matrix environment. In a healthy nucleus pulposus, the proteoglycan-rich matrix possesses a strong ability to hydrate, and water molecules are situated in a relatively ordered microenvironment; consequently, the T2 value is typically high. During the degenerative process, the loss of proteoglycans leads to a reduction in hydration capacity; simultaneously, the arrangement of collagen fibers becomes disordered, and the heterogeneity of the matrix increases, altering

the microenvironment in which water molecules are situated, resulting in a corresponding decrease in T2 values.[18,19] Consequently, T2 mapping can, to a certain extent, quantitatively reflect the hydration status and matrix integrity of the intervertebral disc, and a reduction in these values often indicates early changes in disc degeneration.[20] In clinical practice, T2 mapping supports decisions about conservative treatment. For example, patients with early-stage degeneration and relatively high T2 values may be better suited to physical therapy, medication, or lifestyle interventions to slow disease progression, as this suggests the disc retains a certain degree of hydration and reparative potential,[21] providing clinicians with an objective indicator for assessing treatment efficacy and thereby optimizing treatment plans. It should be emphasized that T2* mapping differs from T2 mapping. The advantage of T2* mapping is that its apparent transverse relaxation time incorporates the intrinsic T2 relaxation of the tissue and accounts for additional phase shifts caused by inhomogeneities in the main magnetic field and magnetization effects; consequently, it is more sensitive to changes related to magnetization. Therefore, T2* mapping is better suited than T2 mapping for detecting magnetic field inhomogeneities and changes in magnetic susceptibility; in the assessment of magnetic susceptibility-related changes such as iron deposition and calcification, as well as certain types of annular tears, T2* mapping can provide supplementary information, contributing to a more comprehensive evaluation of the structural integrity of the intervertebral disc. As the two techniques differ in terms of imaging sequences, physical significance, and factors affecting sensitivity, they should not be used interchangeably or as substitutes for one another.[22,23]

(ii) T1ρ mapping: The T1ρ (T1 in a rotational coordinate system) relaxation time is particularly sensitive to slow motion and chemical exchange between macromolecules (such as proteoglycans) and water molecules. In intervertebral discs, proteoglycans are the key components responsible for maintaining the hydration and biomechanical function of the nucleus pulposus. Unlike T2 mapping, which primarily reflects hydration status and matrix integrity, T1ρ mapping can be more directly correlated with proteoglycans as a biochemical component; studies have shown that T1ρ values are highly correlated with the proteoglycan content in the intervertebral disc and may detect proteoglycan loss earlier than T2 values, reflecting biochemical abnormalities even before morphological changes occur in the tissue.[24,25] This makes T1ρ mapping a powerful tool for assessing early-stage IVDD and monitoring the efficacy of regenerative therapies. In regenerative medicine—such as following stem cell transplantation, platelet-rich plasma injections, or gene therapy—changes in T1ρ values can objectively reflect the synthesis or repair of proteoglycans within the intervertebral disc, helping evaluate treatment efficacy. For example, if T1ρ values increase after treatment, this may indicate increased proteoglycan content and an improved biochemical environment in the intervertebral disc. This helps guide adjustments to subsequent treatment plans, assists clinicians in determining whether regenerative therapy has improved the disc's biochemical environment, and provides patients with personalized prognostic assessments.

(iii) DKI: Traditional diffusion-weighted imaging assumes that water molecules diffuse according to a Gaussian distribution, whereas DKI is no longer limited by this assumption and is capable of quantifying the non-Gaussian diffusion behavior of water molecules, thereby offering the potential to better reflect the complexity and heterogeneity of tissue microstructure. The physical basis for this is that water molecules do not diffuse freely within biological tissues; instead, they are constrained and impeded by complex structures such as cell membranes, organelles, and the extracellular matrix, causing their diffusion to deviate from a Gaussian distribution. In IVDD, extracellular matrix degradation, disorganization of collagen fibers, and alterations in the extracellular space all influence water-diffusion patterns. Commonly used DKI parameters (such as mean kurtosis and fractional anisotropy) help to capture these subtle changes that precede macroscopic morphological alterations, and therefore show some potential for early diagnosis.[26-28] Clinically, DKI may prove valuable in the future for detecting minute structural abnormalities that are difficult to discern on conventional MRI; for example, patients who show no obvious abnormalities on conventional MRI but exhibit abnormal DKI parameters may be at risk of faster degenerative progression or a higher risk of symptom onset. Through DKI, clinicians may identify individuals earlier who need close monitoring or early intervention, enabling preventive treatment or more proactive conservative management to delay or prevent progression to a stage requiring surgery.

(iv) Other cutting-edge technologies: GAG-CEST imaging enables direct and specific imaging of glycosaminoglycans (GAGs) by measuring signal attenuation associated with proton exchange on GAGs, thereby providing a new approach for the non-invasive monitoring of key components of the

extracellular matrix.[29,30] Unlike the morphological semi-quantitative assessment of the Pfirrmann classification, GAG-CEST directly targets GAG—a key biochemical component that maintains the hydration and biomechanical function of the nucleus pulposus—and is therefore able to indicate biochemical abnormalities in the matrix even when there are no obvious morphological changes in the intervertebral disc. This is highly significant for assessing early degeneration and the efficacy of regenerative therapies. Furthermore, magnetic resonance spectroscopy (MRS) technology can detect changes in metabolites within the intervertebral disc, such as lactate, choline, creatine, and lipids. Compared with the Pfirrmann classification, MRS can further reveal metabolic abnormalities in degenerated discs, providing a unique perspective on the biochemical processes of IVDD.[31,32] For example, elevated lactate levels may indicate hypoxia and enhanced glycolysis, reflecting metabolic abnormalities in degenerated intervertebral discs. These techniques complement the Pfirrmann classification—the former focusing on composition and metabolism, whilst the latter providing a morphological baseline—and are expected to offer a more comprehensive clinical basis for the precise diagnosis and personalized treatment of IVDD in the future, particularly in the early stages of the disease and in the assessment of treatment response. Building on this, studies utilizing quantitative MRI have explored the relationship between lumbar disc degeneration and the morphology of paraspinal muscles, emphasizing the significant role of age in this association. As key structures responsible for maintaining lumbar spinal stability and load transfer, changes in the cross-sectional area, degree of fatty infiltration, and functional status of the paraspinal muscles may interact with IVDD progression by influencing the mechanical environment of the intervertebral disc. Consequently, when interpreting quantitative MRI parameters, one should not limit the analysis to the intervertebral disc alone, but should make a comprehensive assessment that takes into account the overall context of spinal degeneration, including age and the degeneration of paraspinal muscles; this provides a more comprehensive imaging perspective for IVDD risk stratification, the formulation of rehabilitation strategies, and the development of personalized treatment plans.[33,34]

Although these quantitative MRI techniques show great promise, they still face numerous challenges in clinical translation and widespread application. First is the issue of standardization. Differences in equipment manufacturers, magnetic field strength, scan parameter settings, and post-processing methods can lead to significant variations in quantitative results, severely affecting data comparability and the conduct of multicenter studies. The modified eight-grade classification system improves the ability to distinguish patients with severe degeneration by refining the assessment of endplates, osteophytes, and the annulus fibrosus. Second is scan duration. Many advanced quantitative MRI sequences, particularly those involving multiparametric acquisition, are time-consuming, increasing patient discomfort from prolonged immobility within the MRI scanner and limiting their application in clinical settings.

2.3. Classification of artificial intelligence and automation

The traditional Pfirrmann classification relies on manual interpretation, which is time-consuming and leads to significant variation between observers, limiting its efficiency and objectivity in clinical practice. AI, particularly deep learning algorithms, offers a powerful solution to this problem. Researchers have developed various convolutional neural network models that can automatically segment the intervertebral disc region in MRI images and perform Pfirrmann grading.[35-37] These AI systems not only significantly improve assessment efficiency by automating the previously time-consuming manual interpretation process, but also reduce subjectivity through standardized algorithms, thereby enhancing the consistency and reproducibility of grading and providing a more reliable basis for clinical diagnosis and research.[38,39] In the future, AI is expected to integrate multimodal imaging data and clinical information to develop more comprehensive predictive models. These will not only enable a more accurate assessment of the extent of disc degeneration and a better prediction of disease progression—thereby facilitating the selection of optimal treatment options for patients at different stages of degeneration—but will also allow for an in-depth analysis of disc repair mechanisms, leading to breakthroughs in the treatment of disc disorders.[40]

Although the techniques mentioned above—such as T1ρ, DKI, GAG-CEST, MRS, and AI-assisted grading—have demonstrated potential for expanding from morphological assessment to the evaluation of composition and microstructure, they still differ fundamentally from established clinical tools. At present, conventional MRI morphological assessment and the Pfirrmann classification remain the primary clinical basis; most of the aforementioned technologies are still in the methodological exploration phase and lack universally recognized clinical decision-making criteria. Consequently, they are currently

better suited as supplementary assessment tools for risk stratification studies or as exploratory tools for monitoring treatment efficacy, rather than as direct determinants of treatment strategies. In clinical practice, the diagnosis and treatment of disc degeneration still require a comprehensive assessment combining imaging findings, symptoms, physical signs, and the patient's individual circumstances.

3. Clinical relevance of Pfirrmann grading for symptoms and treatment response

Despite continuous advancements in imaging assessment technologies, their clinical value ultimately lies in their ability to guide treatment decisions and predict patient prognosis. This section explores the complex relationship between the Pfirrmann grading system, clinical manifestations, and the efficacy of different treatment methods.

3.1. Inconsistency between imaging degeneration and clinical symptoms

The imaging–clinical mismatch has become a well-recognized phenomenon in spinal surgery. Evidence from population-based studies suggests that severe disc degeneration on MRI may be present in healthy individuals with no LBP; conversely, MRI scans of many patients with LBP may show only mild degeneration.[41] This phenomenon suggests that relying solely on morphological grades of degeneration is insufficient to fully explain the mechanisms underlying pain. Further research has revealed that within degenerated intervertebral discs, particularly in areas where the annulus fibrosus is ruptured, there is often abnormal ingrowth of new nerve endings and capillaries; these new nerve fibers contain nociceptors, which underlie pain signaling.[42-44] During the degenerative process, cells release large quantities of inflammatory mediators; these cytokines not only accelerate matrix degradation but also amplify pain perception by directly sensitizing nociceptors.[45,46] Furthermore, pathological changes in the endplates and osteoarthritis of the facet joints associated with IVDD have also been confirmed as significant independent sources of LBP.[47] At the same time, psychosocial factors cannot be overlooked in the development and chronicisation of LBP. Psychosocial variables such as anxiety, depression, pain catastrophizing, fear-avoidance beliefs, and excessive focus on pain have been shown to significantly influence pain perception, functional status, and treatment response, and may even play a role in some individuals independently of the degree of degenerative changes observed on imaging.[48-50] It is therefore evident that LBP development is not attributable to a single factor, but results from the combined action of multiple mechanisms, including IVDD, changes in the endplates, facet joint pathology, neurovascular ingrowth, inflammatory cascades, and psychosocial factors. The Pfirrmann grading system was originally designed to assess signal intensity and morphological characteristics within the intervertebral disc; it cannot capture the neurovascular regeneration and inflammatory cascade reactions directly related to pain generation mentioned above. This fundamentally explains why there is often a discrepancy between this grading system and clinical symptoms. It should be noted that this mismatch does not negate the clinical value of the Pfirrmann grading system; rather, it suggests that its value lies not in directly correlating with pain severity, but in providing differentiated guidance for predicting the prognosis of different treatment approaches. In clinical practice, when conducting a comprehensive assessment of patients with LBP, in addition to considering the Pfirrmann classification, due regard should also be given to changes in the endplates, small joint pathology, the inflammatory status, nerve innervation, and psychosocial factors, thereby enabling a more comprehensive understanding of the source of symptoms and the formulation of individualized treatment strategies.

3.2. The role of the Pfirrmann grading system in predicting the efficacy of conservative treatment

For most patients with LBP, conservative treatment is the preferred approach. The Pfirrmann grading system can predict its efficacy to some extent. A study on lumbar traction therapy utilized T2 mapping to identify that traction significantly increased the T2 values of the disc nucleus in Pfirrmann grades II–IV, and that changes in T2 values were closely correlated with improvements in patients' clinical symptoms (Oswestry disability index/visual analog scale scores). This suggests that conservative treatment may be more effective for moderately degenerated discs where the structure has not yet been destroyed, and there is still potential for "hydration."[51-53] Similarly, in studies evaluating traditional Chinese medical therapies such as acupuncture, the Pfirrmann classification has also been used as the basis for baseline assessment and patient grouping to investigate the impact of varying degrees of degeneration on treatment response.[54-56] However, because the efficacy of conservative treatment is influenced by a variety of factors (such as patient compliance and psychological state), the predictive value of the Pfirrmann classification still requires further high-quality research to confirm.

3.3. The role of the Pfirrmann grading system in predicting the efficacy of surgical and regenerative treatments

When conservative treatment proves ineffective, surgery

becomes a necessary option. Pre-operative Pfirrmann staging is of great significance for the selection of surgical approach and the assessment of prognosis.[57] For example, in decision-making regarding surgery for single-level lumbar disc herniation, non-fusion procedures that preserve mobility have, in long-term follow-up studies, demonstrated an advantage in protecting adjacent segments compared with traditional posterior lumbar interbody fusion; they can reduce the incidence of degeneration in adjacent segments, and this advantage is particularly pronounced in patient groups where degeneration is not yet significant.[58] Furthermore, for annular defects following discoscopic nucleotomy, suture repair techniques are now in clinical use; the aim is to maintain disc height and restore the structural integrity of the annulus fibrosus, thereby reducing the risk of re-herniation and accelerated degeneration. No significant deterioration in the post-operative Pfirrmann classification was observed, which is regarded as one of the radiological indicators of a successful surgical outcome.[59]

In recent years, regenerative therapies aimed at delaying or even reversing the degenerative process have gradually become a research focus in this field. Such therapies primarily include the injection of mesenchymal stem cells, nucleus pulposus cell transplantation, and the local delivery of various growth factors; whether these interventions achieve the desired outcomes is closely related to the biological activity and microenvironmental status within the intervertebral disc.[60,61] In this context, the Pfirrmann classification has become an important screening tool. It is currently widely accepted that the early- to moderate-degeneration stages corresponding to Pfirrmann grades II to III are frequently used for patient selection in regenerative therapy studies; this is primarily based on clinical trial inclusion criteria, basic biological inferences, and limited clinical observations. However, there is a lack of high-quality studies directly comparing treatment responses among patients with different Pfirrmann grades. At this stage, some active host cells remain within the intervertebral disc; the collagen network and proteoglycan matrix are still relatively intact; no significant vascular invasion has yet occurred; and a certain degree of immune tolerance is maintained. Collectively, these conditions provide a relatively favorable environment for the survival, functional integration, and matrix regeneration of implanted exogenous cells or bioactive molecules.[62] A three-year study involved the re-implantation of autologous nucleus pulposus cells, activated *in vitro*, into degenerated intervertebral discs classified as Pfirrmann grade III; the results confirmed that the procedure was well tolerated and demonstrated good safety, with radiological improvements observed in some cases.[63] Furthermore, numerous clinical trials and systematic reviews on mesenchymal stem cell therapy have also included the Pfirrmann grading system as an enrolment criterion; the majority of these studies enrolled participants with moderate degeneration and a preserved disc height of over 50 percent, and during follow-up, changes in classification were used as one of the key radiological criteria for assessing efficacy.[64-67] In contrast to the above, severely degenerated intervertebral discs, as represented by Pfirrmann grades IV to V, exhibit a fundamentally deteriorated internal microenvironment, characterized by a sharp decline in the number of endogenous cells, local acid-base imbalance, reduced oxygen partial pressure, and elevated osmotic pressure, accompanied by the accumulation of large quantities of inflammatory cytokines and catabolic enzymes. The combination of these adverse factors severely impairs the survival and function of transplanted cells, making it difficult to achieve the expected reparative outcomes.[68] Consequently, for patients at this stage, strategies relying solely on the injection of cells or growth factors yield minimal results; a more promising approach involves the use of smart hydrogels capable of modulating the microenvironment, or the combined application of cell transplantation with anti-inflammatory and antioxidant drugs, with the aim of improving the overall quality of the local microenvironment prior to cell implantation[69,70] (Figure 4).

4. Discussion

This paper examines the assessment of IVDD based on the Pfirrmann classification and its relationship with clinical efficacy. Overall, as a well-established and widely used morphological assessment tool, the Pfirrmann classification remains invaluable for describing the pathological progression of IVDD, providing a unified framework for communication in both clinical practice and research. However, its limitations cannot be overlooked: IVDD is, by its very nature, a complex, multi-level process involving molecular, cellular, and tissue levels, whereas the Pfirrmann classification simplifies this into discrete grades, making it difficult to fully reflect the subtle differences within the degenerative process; more importantly, it fails to account for the complex biological mechanisms underlying discogenic pain. In fact, disc-related pain is not merely the result of structural degeneration but is also closely associated with biochemical and neurobiological changes, such as the release of inflammatory mediators, nerve ingrowth, and sensitization; this fundamentally explains the common discrepancy between the degree of degenerative change observed on imaging and the manifestation of pain.[71] Consequently, the relationship between the Pfirrmann classification and clinical efficacy

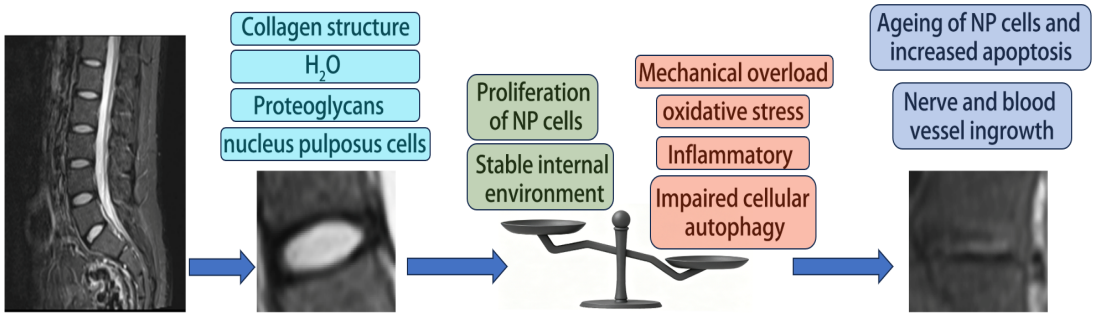


Figure 4. Pathological process of intervertebral disc degeneration
Abbreviation: NP: Nucleus pulposus.

is clearly context-dependent and does not serve as a universal predictive indicator applicable to all treatment strategies. In comparison, its guidance value is more prominent in regenerative therapies, as it helps identify patients whose biological environment remains intact and who are most likely to benefit from cellular or biofactor interventions, thereby optimizing treatment selection and patient expectation management.[62]

The key to achieving a closer alignment between imaging and clinical presentation lies in establishing a comprehensive, multi-parameter assessment system based on the Pfirrmann classification. This system should integrate quantitative MRI parameters, as these quantitative MRI indicators are expected to serve as biomarkers that are more sensitive than traditional classifications and more closely correlated with clinical symptoms.[12,31] The assessment framework should also incorporate clinical information such as detailed medical history, physical examination, and pain questionnaires to classify patients by clinical phenotype, while also accounting for important prognostic variables such as vertebral bone quality, the condition of the facet joints, and psychosocial factors.[72] Building on this, AI will become a key tool for achieving multidimensional data integration and precise predictions. By using deep learning models to analyze imaging, clinical, and—in the future—potentially genomic data in conjunction, AI is expected to identify complex patterns that are difficult for humans to detect, and to build intelligent decision-support systems tailored to specific patients and specific treatment regimens, thereby driving the evolution of IVDD assessment from a simple morphological description towards precise stratification and personalized treatment.

5. Limitations

The analysis in this paper regarding the relationship between the Pfirrmann classification and the efficacy of conservative, surgical, and regenerative treatments is largely based on retrospective studies, small-sample clinical trials, and indirect evidence; it has yet to be validated by large-scale, multicenter, prospective studies, and in particular, there is a lack of high-quality evidence directly comparing treatment responses in patients with different Pfirrmann classifications. Furthermore, this paper has not systematically incorporated biomarkers such as genomics and proteomics, or psychosocial factors; the proposed multi-parameter integrated model remains conceptual. Future research should conduct multicenter prospective cohort studies, establish uniform scanning and post-processing standards, and validate the clinical value of quantitative MRI and AI in the early diagnosis of IVDD, treatment outcome prediction, and patient stratification.

The assessment of IVDD is moving away from a single morphological grading system toward a new era characterized by multi-parameter, quantitative, and intelligent approaches. Combining the Pfirrmann classification with advanced quantitative MRI techniques, and leveraging AI to integrate multi-source data, will enable us to gain a deeper understanding of each patient's unique pathophysiological state. This comprehensive assessment model will not only predict treatment responses more accurately but will also drive the development of precision treatment strategies tailored to different stages of degeneration and clinical phenotypes, ultimately delivering more effective, personalized treatment plans for a wide range of patients with degenerative disc disease.

6. Conclusion

As a classic method for assessing the severity of IVDD, the Pfirrmann classification system has made significant contributions to clinical diagnosis and scientific research. However, the lack of correlation between this classification

and clinical symptoms and treatment outcomes has limited its predictive value in personalized treatment decision-making. Research indicates that the association between the Pfirrmann classification and clinical efficacy is not static but varies by treatment modality. It demonstrates high diagnostic value in screening patients suitable for regenerative therapy, providing crucial radiological evidence for determining the optimal timing of treatment. For conservative and conventional surgical treatments, its predictive value is relatively limited, and a comprehensive assessment incorporating additional clinical information is required.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Chao Ge, Weimin Wang
Funding acquisition: Weimin Wang, Chao Ge, Pengtao Huang
Project administration: Chao Ge, Zihan Qi
Supervision: Weimin Wang, Pengtao Huang
Visualization: Mingwei Wang, Tao Wang, Pengtao Huang
Writing–original draft: Chao Ge, Qiujing Hao
Writing–review & editing: Bifeng Fu, Mingwei Wang

Ethics approval and consent to participate

Not applicable.

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AI tools statement

The authors used DeepSeek-V3 solely for language editing. The tool was not used for data analysis, result interpretation, or generation of scientific conclusions. All AI-assisted content was reviewed, verified, and edited by the authors, who take full responsibility for the accuracy, integrity, and originality of the manuscript. No AI tool is listed as an author.

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